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Method and apparatus for locating devices

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Method and Apparatus for locating devicesTechnical Field

The present invention relates to a method and apparatus for locating devices. It 5 particularly relates to locating relatively simple and inexpensive devices which have the ability to communicate with one another in a wireless manner, provided the devices are located sufficiently close to one another to be "in range", when such devices are located with a sufficiently high distribution density that the devices are able to form an "ad-hoc" network by which the devices may communicate with one 10 another and with external devices having an appropriate connection to the wireless ad-hoc network.

Background to the Invention and Prior Art

Wireless ad-hoc networks, which are self-organising, rapidly deployable and which 15 require no fixed infra-structure since they are made solely (or at least largely) of self-contained wireless devices, are known and have been the subject of considerable research in recent times. However, such networks as proposed heretofore have been restricted in their approaches to obtaining positional information about individual devices within the network. In the main, three different types of approach have been 20 adopted: approach 1 is simply not to provide positional information about individual devices within the network; approach 2 is to rely on such information being known *a priori* (eg by having been carefully placed in pre-ordained positions) and not being liable to change in an unpredictable manner; approach 3 is to use devices which include Global Positioning Systems (GPS's). In certain applications for such networks 25 however, none of the above approaches is ideal. For example, in an application for sensing ocean conditions using an ad-hoc network of free floating sensors the first approach is not ideal because the sense data from each sensor is only valuable if accompanied with the position of the sensor at the time the data was recorded; the second approach is not tenable because the sensors will move with the ocean 30 currents in an unpredictable manner (even assuming their initial placement was known); and the third approach is non-ideal because of the expense of supplying each sensor with a GPS.

In "GPS-free positioning in mobile ad hoc networks" by Srdjan Capkun, et al., *Cluster Computing, Volume 5, # 2, April 2002* the authors describe an algorithm for permitting devices within a wireless ad-hoc network to obtain relative positional information without the use of any GPS containing devices, using only information

5 about the distances between devices in range of one another (which information, it is said, can be found using a Time of Arrival (TOA) or similar range finding method). The paper mentions that the relative positional information could be associated with a geographical coordinate system only "if the algorithm is used along with some GPS-capable devices." However, it does not mention how this would be done. It also

10 points out that for some applications (of particular concern to the authors) purely relative positional information is sufficient. The main drawback with the proposed method is that it does not scale well to large systems. The number of communications that each node is required to make increases as the number of nodes in the network increases. This means that beyond small networks the time

15 needed and the processor power required becomes restrictive. Additionally, the calculations required of each device to execute the described algorithm are relatively arduous for very simple devices and therefore likely to be costly in terms of power consumption; additionally, the complexity has a negative impact on the speed with which the relative positions of the devices can be recalculated in the event of

20 movement of the devices.

An alternative approach has also been considered in the field of ad-hoc wireless networks which, however, involves the use of base-stations for location purposes. In this approach (which may be thought of as a semi-ad-hoc semi-cellular approach)

25 simple devices are able to communicate with one another to navigate data through the network (rather than just communicating with base stations as in purely cellular systems), but use only the base stations for location determination purposes (ie they do not attempt to determine their location from the locations of neighbouring simple devices only from neighbouring base stations). This approach has the disadvantage

30 that a relatively large number of the more expensive base stations are required throughout the network.

Summary of the Invention

According to a first aspect of the present invention, there is provided a method of obtaining positional information about individual wireless devices within a wireless ad-hoc network including a plurality of position determining devices in which each 5 position determining device includes means for estimating the distance between itself and any other similar device forming part of the network which is within range, the method including the steps of:

- i) each position determining device receiving a broadcast message from each other similar device in range specifying, if known, the respective broadcasting 10 device's position or series of possible positions;
- ii) each position determining device attempting to measure its distance from each other similar device in range;
- iii) each position determining device calculating, if it has sufficient information, its position, or a series of possible positions and storing this information; 15 and
- iv) each position determining device broadcasting to each other similar device in range, if known, its position or series of possible positions determined in step iii.

This method works very well where the ad-hoc network includes a small percentage 20 of devices which have some initial knowledge about their position. This may, for example, be achieved either by having some devices placed in fixed known locations or by having some devices which include a GPS. Since only a small fraction of the total devices used need to be specially treated in this way, there is only a very small overall cost increase compared to a network in which none of the devices are 25 specially treated in this way.

Note that steps (i) and (ii) may be performed in any order (or even simultaneously or in an overlapping or interleaved way, and may be different for different devices).

30 Preferably, the above described steps are repeated on a regular basis. However, in some applications the devices will remain in fixed locations and it is not therefore necessary to repeat all of these steps at each repetition or iteration. For example, in such a circumstance the relative distances between neighbouring nodes would only

need to be determined once. Also, once a device has identified its actual position it will only need to repeat the final step (iv), and this only until all of its neighbouring devices have established their own locations, or the network decides that no further elimination of incorrect possible locations can be removed because of the particular  
5 distribution of the devices within the network.

Thus one embodiment of the invention takes a wireless ad-hoc network of nodes that each have a set range of communication. Within this network some nodes have information about their location (it is envisaged that each of these is either carefully  
10 placed and fixed at a certain location or belongs to a small sub-set of more expensive devices each of which is equipped with a GPS receiver). The nodes in the network then determine their distance to other neighbouring nodes that are within range of communication (exactly how would depend on the environment that they are in but something along the line of sonar or radar is envisaged). By solving trigonometric  
15 equations, it is possible for a node that does not know it's location, but is within range of two nodes that do know their location, to solve the equations of circles and determine that it is located in one of two possible locations. This information can then propagate through the network allowing other nodes to determine their position to one of several locations. When positional information from other nodes also  
20 propagates through the network it becomes clear that some of the possible positions for a node of unknown location are inconsistent with all the data. The nodes thus discard these inconsistent positions to leave fewer possible positions and in some cases 1 possible position, which is the correct location of the node. The present embodiment thus allows nodes to effectively locate themselves relative to each other  
25 in a very low-cost fashion, and then use partial information about their absolute position to enable a proportion of nodes in the network (seemingly dependent on the density of nodes in the network) to locate themselves accurately and absolutely. It applies to both fixed (non-moving) and fully mobile networks equally, with mobile networks effectively re-calculating the nodes' positions at regular intervals.

30

Preferably, the network includes at least three devices which have *a priori* knowledge about their position (or their possible positions) at least two of which are located sufficiently close together to be in range of a third device.

In one preferred strategy for distributing the devices of the network, there are a small number (certainly < 10%, sometimes as low as  $\leq 5\%$ ) of 'gps' devices (ie devices having *a priori* positional information) that are either in planned locations or are

5 distributed so that there are very few redundant devices giving excess information to nodes that don't need it. In another preferred strategy, there is a larger number (maybe as high as 25%) of gps devices that are completely randomly distributed in exactly the same way as the other non-gps devices. In both cases there is a degree of trade-off, the denser the network (i.e. the greater the number of devices that have

10 no information about their initial location) the lower the number of 'gps' devices that are required.

By the term possible positions, or series of possible positions, it is meant that one of the possible positions is the actual position of the device (within a certain margin of

15 error) but the device does not (at that particular time at least) know which of the possible positions is the correct one.

In a preferred embodiment, all of the devices are position determining devices in the sense that they will each attempt to identify their position based on the information

20 broadcast to them from neighbouring devices in the network together with range information determined using whatever distance detection mechanisms they possess. However, the possibility of including certain devices which form part of the network but which make no effort to determine their own position is not excluded. Similarly, for the purposes of this specification, devices which have some *a priori* knowledge

25 about their position (and thus do not need to determine their position according to the above set out method) are intended to be covered by the term "position determining devices."

Further preferred features of the first aspect of the present invention are set out in

30 the claims dependent upon claim 1.

According to a second aspect of the present invention, there is provided a method of operating an individual device as set out in claim 10.

According to a third aspect of the present invention, there is provided a device as set out in claim 11.

5 Brief Description of the Drawings

In order that the present invention may be better understood, embodiments thereof will now be described, by way of example only, with reference to the accompanying drawings in which:

Figure 1 is a diagrammatic representation of a wireless ad-hoc network prior 10 to commencement of a procedure for locating the positions of the devices within the network;

Figure 2 is a diagrammatic representation of the wireless network of Figure 1 after a first iteration of the position determination procedure;

Figure 3 is a diagrammatic representation of the wireless network of Figure 1 15 after a second iteration of the position determination procedure;

Figure 4 is a diagrammatic representation of the wireless network of Figure 1 after a third iteration of the position determination procedure;

Figure 5 is a diagrammatic representation of the wireless network of Figure 1 after a fourth iteration of the position determination procedure;

20 Figure 6 is a diagrammatic representation of the wireless network of Figure 1 after a fifth iteration of the position determination procedure;

Figure 7 is a diagrammatic representation of the wireless network of Figure 1 after a sixth iteration of the position determination procedure; and

25 Figure 8 is a schematic diagram of an individual device of the wireless network of Figure 1.

Detailed Description of the Embodiments

The first embodiment to be described is of a small wireless ad-hoc network comprising twelve position determining devices, only three of which contain GPS's, 30 and which are able to determine the position of most of the devices within six iterations of the position determining algorithm described below. The described embodiment, comprising only twelve devices, could be used for monitoring a small body of water. However, it will be apparent to a person skilled in the art that the

described embodiment could easily be scaled up for use in monitoring a very large body of water such as a sea or ocean, by including many more simple devices (no more of which would, in theory, require in-built GPS's).

- 5 In overview, in the present example embodiment, three of the devices include GPS's and these broadcast their location at the first step of each of the required six iterations. At approximately the same time, each of the other devices determines its distance from each other device with which it is in range. Using this information, at each iteration each device attempts to identify its location or a series of possible
- 10 locations and then broadcasts such locations or possible locations at the start of each subsequent iteration. As devices begin to receive more information about possible positions of their neighbouring devices, they are firstly able to generate a series of possible positions themselves and then are able to eliminate impossible positions until after only six iterations in the present example, six of the nine devices which
- 15 originally had no information about their whereabouts identify their exact position, one narrows down the possibilities to one of two possible positions and the remaining two narrow down the possibilities to one of four possible positions.

Thus, Figure 1 illustrates the wireless ad-hoc network of twelve position determining devices 1-12 prior to any iterations of the procedure for determining the locations of the devices. The behaviour of the network has been simulated and Figures 2 to 7 illustrate the evolution of the network during successive iterations of the position determination procedure according to the simulation. Each device 1-12 can also be thought of as forming a node of the network as a whole. Therefore the term node

25 may be used in place of the term device throughout this document, when referring to the devices' role as nodes.

In the initial state of the network illustrated in Figure 1, only three of the devices 1, 2, and 3 have *a priori* knowledge of their position. In the present embodiment, these

30 three devices 1, 2 and 3 have such knowledge because they each have an inbuilt GPS. For purposes of illustration, the range 1a, 2a, 3a, of each of these devices 1, 2, 3 is shown in each of Figures 1 to 7. The ranges of the other devices 4-12 is

omitted for the sake of clarity. However, the ranges of all of the devices (including those with and without in-built GPS's) are equal.

As will be apparent to a person skilled in the art, the communications between the 5 devices can be carried out in a number of well known manners. The details of such methods of communication will not be described here in detail. 'Ad Hoc networking', Charles E. Perkins, Pub. Adison Wesley, Dec. 2001 and the references cited therein provide a detailed description of some suitable such methods. Similarly, there are many well known methods of determining the distance from one device to another, 10 such as, for example, the Radio Acoustic Ranging (RAR) method. Implementations of this method are well known and will not be discussed here in detail. Chapter 6 of 'Hydrographic Manual' by Commander K. T. Adams, Special publication of US dept. of commerce, Coast and geodetic survey published by US Govt. printing office, 1942 and the references cited therein provide a detailed description of RAR.

15

#### **First Iteration**

Step 1: the first step of the procedure is for the GPS containing devices 1, 2 and 3 to broadcast their (initially known) positions to all of the devices in range. Thus device 1 broadcasts its position to devices 4 and 9-11. Device 2 broadcasts its position to 20 devices 5, 6 and 7 (and also to device 3 which, in the present embodiment, ignores this information for the purposes of position determination since it is able to identify its position via its in-built GPS). Finally, device 3 broadcasts its position to devices 6 and 7 (and also device 2, see comment above).

25 Step 2: the second step is for each device to determine its distance from each neighbouring device which is within range. Note that in the present embodiment, each device only attempts to determine its distance from devices with which it can communicate directly. In alternative embodiments, however, if the range determining mechanism can act over a greater distance than the communication device (as in the 30 present embodiment, see the discussion below with reference to Figure 7) it may be advantageous to permit devices having difficulty locating themselves using only their in-range neighbours to obtain distance information with respect to more remote, out

of range devices and to obtain the position information from those out of range devices via intermediate nodes which are in range.

In the present embodiment, the devices 1, 2, 3 having in-built GPS's do not gather 5 this information since they do not need to determine their positions. Device 4 determines its distance from nodes 1, 5, 8 and 12; Device 5 determines its distance from nodes 11, 4, 12, 8, 6 and 2; etc. (note for a fuller listing of the positions of the nodes, the nodes within range of one another and the details of the calculations performed by the nodes at each iteration of the method, see the Appendix, which 10 sets out all of the details in note form).

Step 3: in the third step each device determines if it has sufficient information to determine either its position or a series of possible positions. In the present embodiment, this requires knowledge of the position, or series of possible positions, 15 of two or more neighbouring devices. In the present example at the first iteration, this is the case only for nodes 6 and 7 (node 5 being just outside the range of node 3) which are in range of both nodes 2 and 3 which (since they include GPS's) have an initial knowledge of their position.

20 If a device determines that it has sufficient information to calculate its position or a series of possible positions it does so (in embodiments involving a very large number of devices it is possible that very large numbers of possible positions might have to be calculated and stored; such embodiments may therefore include a threshold such that if the series of possible positions includes more than a predetermined number of 25 such possible positions then the possible positions are neither stored nor transmitted at the following step 1, in the hope that after subsequent iterations the number of possible positions will have reduced to below the threshold amount).

In the present embodiment, this is achieved by solving the following equations:

30

$$(X-X_{N1})^2 + (Y-Y_{N1}) = R_{N1}^2$$

$$(X-X_{N2})^2 + (Y-Y_{N2}) = R_{N2}^2$$

where  $X_{N1}$  &  $Y_{N1}$  and  $X_{N2}$  &  $Y_{N2}$  are the broadcast X and Y coordinates of a pair of neighbouring nodes N1 and N2 which have broadcast their X and Y coordinates during the preceding Step 1. The solution of these simultaneous equations will result in two possible positions of the node in question, a correct and an incorrect solution

5 (though these may in theory coincide when the device in question and the neighbouring nodes all lie on a straight line). The incorrect solution is symmetrical with the correct solution along a line of symmetry connecting the two neighbouring nodes. Note that if information as to the position and distance from the node in question of a third neighbouring node were known, it would be possible to eliminate

10 the incorrect solution. As will be appreciated from the specific descriptions of the calculations performed by devices in the present example given below, this combination of determining possible positions and comparing these possible positions with known ranges from third devices (in combination with their possible positions) it is possible to maintain and update lists of possible positions of each node.

15

Thus in the present example, node 6 determines that it should solve the following equations:

$$(X - 118)^2 + (Y - 285)^2 = 129^2 \quad (\text{Node 2})$$

20  $(X - 88)^2 + (Y - 308)^2 = 132^2 \quad (\text{Node 3})$

From which it determines that either  $X=32$ ,  $Y=189$  (which is the correct solution) or  $X=188$ ,  $Y=393$  (which is the incorrect solution).

25 At this first iteration there is no third neighbouring node from which node 6 can attempt to eliminate one of these two possible solutions. Thus it maintains both of these and proceeds to the next step. Node 7 performs a similar set of calculations to determine that either  $X_{N7}=28$ ,  $Y_{N7}=336$  or  $X_{N7}=45$ ,  $Y_{N7}=359$ .

30 The third step represents the final step of the first iteration.

#### Second Iteration

First step: Every device which has information about its position or a series of possible positions broadcasts this information to all neighbouring devices in range. Thus nodes 1, 2 and 3 broadcast to the same nodes as in the first iteration (note if they have moved, the new positions of these nodes will be used by the neighbouring

5 nodes 6 and 7 to update their series of possible positions based on the positions and distances of these nodes), including node 2 broadcasting to node 5. Additionally, node 6 broadcasts its pair of possible positions to nodes 5, 8 and 12 (as well as nodes 2 and 3 which ignore the information since they have in-built GPS's and node 7 which cannot use this information to eliminate impossible positions because node

10 6's information derives from the same nodes - nodes 2 and 3 - as for node 7, thus preventing any possibilities from being ruled out). Node 7 is only in range of nodes 2, 3 and 6. It does broadcast to all of these nodes but it does not assist any of them to determine their location more accurately. The fact that nodes 6 and 7 have determined and are broadcasting a series of possible positions is indicated on Figure

15 2 by replacing the diamonds representing nodes which have no positional information with squares surrounding crosses.

Second step: All of the devices re-measure their distance from neighbouring nodes as before. In the simulation of the present example, the devices do not move and so

20 this step will be identical in all respects in each iteration and will not therefore be further described in subsequent iterations.

Third step: Devices 6 and 7 will recalculate their possible positions in the same way as in the second step in the first iteration with exactly the same results (since the

25 devices are held stationary in the present example as simulated). However, device 5 now has sufficient information to attempt to calculate a series of possible positions based on the position information received from nodes 6 and 2. It derives four possible positions in total, two from assuming node 6 is in one of its possible positions and two from assuming node 6 is in the other of its possible positions (see

30 the Appendix for the exact values calculated by node 5).

### Third Iteration

First step: The devices re-broadcast their position information if known. The only difference from the preceding iteration here is that node 5 has a series of four possible positions which it broadcasts to nodes 2, 4, 6, 8, 11 and 12. This is 5 illustrated in Figure 3 by having changed the symbol used to indicate node 5. Nodes 2 and 6 effectively ignore this information as it cannot assist them in improving their positional information. However, the broadcast information from node 5 to nodes 4, 8, 11 and 12 means that each of these nodes is now in range of two nodes which have broadcast to them positional information (broadcasting nodes 1 and 5 are in 10 range of nodes 4 and 11; broadcasting nodes 5 and 6 are in range of nodes 8 and 12).

Second step: As before, each device determines its distance from each in-range neighbour.

15

Third step: The non-GPS nodes which already have some positional information (ie nodes 5, 6 and 7) recalculate their possible positions. In the present example this leads to the same results as in the previous iteration because they have no new information and all of the nodes are static. The non-GPS nodes which received 20 sufficient information to calculate their possible positions for the first time in the first step of this iteration (ie nodes 4, 11, 8 and 12) calculate their possible positions for the first time. Nodes 4 and 11 obtain eight possible positions (see Appendix 1 for details), two for each possible position of node 5 (note that node 1 is a GPS node and thus has only 1 possible position). However, four of the possible positions of 25 node 4 calculated in this way are complex. This corresponds to two of the possible positions of node 5 being unfeasibly faraway from node 1 given the known distance of node 4 from both node 1 and node 5 (the circles surrounding the possible positions of nodes 1 and 5 having radius corresponding to the determined distance between node 4 and nodes 1 and 5 respectively do not intersect for these two 30 unfeasible possible positions of node 5). Similarly, six of the possible positions of node 11 calculated in this way are complex (corresponding to three of the possible positions of node 5 being unfeasible), leaving node 11 with only two possible positions (note this effectively narrows down the number of possible positions of

node 5 to 1 position - node 5 will be able to determine this itself as soon as it receives the possible positions of node 11 at step 1 of the following iteration).

Nodes 8 and 12 obtain sixteen possible positions, two for each of the eight possible 5 combinations of the four possible positions of node 5 and the two possible positions of node 6. However, in both cases half of these combinations of possible positions of nodes 5 and 6 give rise to complex solutions and hence correspond to unfeasible combinations, reducing the number of possible positions of nodes 8 and 12 to eight each (see the Appendix for details).

10

#### Fourth Iteration

Step 1: In this iteration, all of nodes 1, 2, 3, 4, 5, 6, 7, 8, 11 and 12 now have some information about their position (ie one or more possible positions) which they broadcast to all of their neighbours in range. This is illustrated in Figure 4 in which 15 all of nodes 4, 5, 6, 7, 8, 11 and 12 are represented by the square surrounding a cross marking which indicates that these devices are all broadcasting a series of possible positions. This means that nodes 9 and 10 receive broadcasts from nodes 1 and 11 so that these two devices will be able to determine a series of possible positions for the first time in step 3. Additionally, nodes 4, 5, 8 and 12 receive 20 broadcasts from sufficiently many other nodes that they are able to eliminate all but the correct solutions from amongst the possible locations derived from just two of the total number of nodes used to determine a series of possible positions.

Step 2: As before, each device determines its distance from each in-range 25 neighbour.

Step 3: Devices 9 and 10 calculate at this step for the first time a series of four possible positions each using the positional information broadcast by both of nodes 1 and 11. The four possible positions derive from two possibilities in respect of each 30 of the two broadcast possible positions of node 11.

Device 5 receives the two possible positions of node 11 for the first time and uses this information to eliminate all but the correct position from its series of four

possible positions determined (as in the previous iteration) from the information received from nodes 2 and 6, to thus arrive at its actual position.

Device 4 receives all of the possible positions of nodes 8 and 12 and uses these to  
5 eliminate all but the correct position from its series of four possible positions determined from the information received from nodes 1 and 5.

Device 8 receives all of the possible positions of nodes 4, 5, 6 and 12. In this case, device 8 arbitrarily decides to obtain a series of sixteen possible locations (only six of  
10 which are real) using the possible positions of nodes 4 and 6 and then to use the possible positions of nodes 5 and 12 to eliminate all but the correct position from the (real) six possible locations.

Device 12 receives all of the possible positions of nodes 4, 5, 6 and 8. In this case, device 12 arbitrarily decides to use nodes 4 and 6 to derive a series of sixteen possible positions of which twelve are eliminated straight away as they give complex positions and the remaining three are eliminated as incompatible with any of the possible positions of either of nodes 5 or 8 as broadcast to device 12 during step 1 of this iteration.

20

#### **Fifth Iteration**

Step 1: At this point, all of the devices have some positional information and thus all of the devices broadcast this positional information to all of the devices in range. Furthermore, devices 4, 5, 8 and 12 have identified their actual position (as opposed  
25 to a series of possible positions) and these nodes are therefore indicated in Figure 5 by large solid squares.

Step 2: As before, each device determines its distance from each in-range neighbour.

30

Step 3: As is evident from Figure 5, node 6 is now in range of at least three neighbouring nodes which have identified their position (nodes 2, 3, 5, 8 and 12).

This enables device 6 to determine its own position uniquely. In this case it does this by again obtaining a pair of possible positions from the information received from nodes 2 and 3 and then eliminating the incorrect solution by comparing the distance to any of the other nodes whose position is known (ie any of nodes 5, 8 or 12) as 5 calculated using the pair of possible positions for device 6 just calculated, with the actual distance to the node as determined in step 2.

#### Sixth Iteration

Step 1: As before, all of the nodes broadcast their position information to every 10 node in range. The only difference from the corresponding step 1 in the preceding iteration is that in this iteration device 6 has now identified its actual position. This information is broadcast to node 7 (in addition to the other nodes which are in range of node 6).

15 Step 2: As before, each device determines its distance from each in-range neighbour.

Step 3: Node 7 now has three nodes in range which have all broadcast a single position to node 7 which can therefore determine its own position uniquely (ie removing the ambiguity in the position of node 6 enables node 7 to remove the 20 ambiguity from its own position). The other devices perform the same calculations as before to reconfirm their own positions (or series of possible positions in the case of nodes 11, 10 and 9). Note that in the present example where there is no movement of the nodes, the situation is now static and no further nodes will be able to improve their knowledge of their position in subsequent iterations. This position is 25 illustrated in Figure 7 in which nodes 9, 10 and 11 are indicated as broadcasting a series of possible positions at each iteration after the sixth (by use of the square symbol surrounding a cross) whilst all of the remaining non-GPS nodes are indicated as broadcasting their actual position at each subsequent iteration (by use of a larger solid square).

### Description of an individual Device

Figure 8 illustrates an individual one, 4, of the non-GPS devices 4-12 in greater detail (note that in the present embodiment, all of the non-GPS devices are identical to one another, while the GPS devices 1-3 are similar except that they include a GPS device). In alternative embodiments however it may be advantageous to provide the more expensive GPS devices with other additional features over and above the standard non-GPS devices, which features are required in only a minority of the devices.

10

As shown in Figure 8, the device 4, comprises a water-proof casing 13 having the shape of an inverted cone with a large disk-shaped base. Within the cone-part of the casing 13 there is an annular ballast 14 which ensures that, in use, the device floats with the cone-part submerged beneath the surface of the water while the base part floats above the surface of the water. Mounted within the base part is an annular control and power source part 16; this contains a battery as a source of power and various electronic modules, for controlling the transmission and reception of various signals from and to the device 4, described in greater detail below. Mounted at the centre of the top surface of the base-part of the casing 13 is an aerial 18; this choice of location ensures that the aerial 18 is generally above the surface of the water on which the device is floating when in use. The device 4 also includes a sensor part 19 which includes a sonar receiver and, in the present embodiment, a temperature sensor, located towards the point of the cone-part to ensure that it is always located beneath the surface of the water. Located in the point of the cone part is a sonar transmitter 20 for radiating sonic waves. The aerial 18, sensor part 19 and sonar transmitter 20 are all connected to the control and power source part 16 via suitable connecting wires 21.

30 As mentioned above, the devices determine their range from one another using the Radio Acoustic Ranging (RAR) method referred to above. This method essentially involves a device transmitting a radio wave via aerial 18 and a sound wave via the

sonar transmitter simultaneously. The neighbouring devices which are in range detect the incoming radio signal and then measure the time elapsed before they receive the sound wave signal. A simple velocity over time calculation then gives rise to the distance between the transmitting and receiving devices.

5

As will be apparent to a person skilled in the art, the control and power source part 16 includes circuitry for transmitting and receiving signal over the air interface between neighbouring devices via their aerials 18, control circuitry for activating the sonar transmitter 20 and processing circuitry for processing signals received from the sensor part 19 to detect when a sound wave is received and also the temperature of the water adjacent to the sensor part 19. The processing circuitry is also able to control the device to carry out the various steps of the positioning protocol described above, including the necessary digital processing, storage and timing means.

## 15 Variations

In embodiments where the devices move, knowledge of the maximum expected speed can advantageously be used to help eliminate unlikely possible solutions as devices come in and out of range of one another.

20 Instead of having aerials or other range finding devices which transmit and/or receive signals equally well in all directions, it would be possible to use non-symmetrical devices to reduce the ambiguity of the position of nodes. For example, in one embodiment, each node has two transmitters and receivers, each of which is able to transmit/receive signals from a sector of a circle such that the node is able to 25 transmit/receive information from all directions except for a small portion at the front and back where transmission does not cover to prevent interference. Thus by knowing the range to other nodes, node orientation and which side of those nodes the node being located lies on, similar equations can be solved to determine position of a node. The advantage of this approach is that there is less ambiguity in the 30 possible position of the node. However, there is a chance that nodes which are within range of one another will not be able to communicate due to the "black spot" at both the front and the back of each node.

Instead of relying solely on range information, the devices could include some means of determining a bearing from one or more nodes with which they are able to communicate (possibly indirectly through the network) or from completely independent objects at known positions (ie beacons). In such a case, each node will 5 be able to locate itself with fewer neighbouring nodes. However, such bearing determination means are likely to increase the cost of individual devices.

An alternative application for these devices would be in monitoring active volcanoes. In such an application, a number of devices can be carefully placed in selected 10 locations and programmed in with their locations (these would then replace the GPS devices of the above described embodiment). The remaining devices may then be randomly dispersed from say a helicopter or aeroplane flying over the mouth of the volcano. Although some devices will inevitably perish in the adverse conditions, it is probable that sufficient can survive to form an ad-hoc network and to report back to 15 the outside (carefully located) devices which can then forward on useful information to a remote station where the data can be processed.

There are many possible applications for devices as above described such as, for example, employee identity cards which continually locate the wearer and update 20 their position to a central computer, or traffic monitoring systems where such a device is located in a number of vehicles, and traffic jams can be detected and avoided, etc.

Appendix

node 1 possn is 275, 76 *(fixed 'gps' node)*  
 node 2 possn is 118, 285 *(fixed 'gps' node)*  
 5 node 3 possn is 88, 308 *(fixed 'gps' node)*  
 node 4 possn is 127, 64  
 node 5 possn is 148, 170  
 node 6 possn is 32, 189  
 node 7 possn is 28, 336  
 10 node 8 possn is 23, 117  
 node 9 possn is 366, 147  
 node 10 possn is 309, 131  
 node 11 possn is 287, 122  
 node 12 possn is 65, 131  
 15 total # of nodes visible to node 4 is 4 *(they are nodes 1,5,8 & 12)*  
 total # of nodes visible to node 5 is 6 *(they are nodes 11,4,12,8,6 & 2)*  
 total # of nodes visible to node 6 is 6 *(they are nodes 8,7,2,3,5 & 12)*  
 total # of nodes visible to node 7 is 3 *(they are nodes 2,3 & 6)*  
 total # of nodes visible to node 8 is 4 *(they are nodes 6,5,12 & 4)*  
 20 total # of nodes visible to node 9 is 3 *(they are nodes 1,10 & 11)*  
 total # of nodes visible to node 10 is 3 *(they are nodes 1,9, 11)*  
 total # of nodes visible to node 11 is 4 *(they are nodes 5,1,10 & 9)*  
 total # of nodes visible to node 12 is 4 *(they are nodes 4,8,6 & 5)*

25 *First round of location determination:*

node 6 locating...  
 from nodes 2 & 3 node 6 located at either:  
 $x=32, y=189$  or  $x=188, y=393$

30

node 7 locating...  
 from nodes 2 & 3 node 7 located at either:  
 $x=28, y=336$  or  $x=45, y=359$

UPDATING.....

Node 1 already fixed near  $x = 275, y = 76$

Node 2 already fixed near  $x = 118, y = 285$

5 Node 3 already fixed near  $x = 88, y = 308$

updating node 6s # of positions to 2  $(32, 189; 188, 393)$

updating node 7s # of positions to 2  $(28, 336; 45, 359)$

10 *Second round of location determination:*

node 5 locating...

from nodes 2 & 6 node 5 located at either: *(posn 1(of 1) of node 2 and posn 1(of 2)*

15 *node 6)*

$x = 148, y = 170$  or  $x = 0, y = 302$

from nodes 2 & 6 node 5 located at either: *(posn 1(of 1) of node 2 and posn 2(of 2)*

*node 6)*

$x = 71, y = 394$  or  $x = 237, y = 286$

20

node 6 locating...

from nodes 2 & 3 node 6 located at either:

$x = 32, y = 189$  or  $x = 188, y = 393$

25 node 7 locating...

from nodes 2 & 3 node 7 located at either:

$x = 28, y = 336$  or  $x = 45, y = 359$

UPDATING.....

30 Node 1 already fixed near  $x = 275, y = 76$

Node 2 already fixed near  $x = 118, y = 285$

Node 3 already fixed near  $x = 88, y = 308$

updating node 5s # of positions to 4  $(148, 170; 0, 302; 71, 394; 237, 286)$

updating node 6s # of positions to 2      (32,189; 188,393)  
 updating node 7s # of positions to 2      (28,336; 45,359)  
 located = 3, partial = 3

**5 Third round of location determination**

node 4 locating...

from nodes 1 & 5 node 4 located at either:      (*posn 1(of 1) of node 1 and posn 1(of 4) of node 5*)

10   x = 127, y = 64 or x = 243, y = 221

from nodes 1 & 5 node 4 located at either:      (*posn 1(of 1) of node 1 and posn 4(of 4) of node 5*)

x = 183, y = 192 or x = 320, y = 217

15   (*for positions 2 & 3 of node 5 there are no intersections of the circles and hence no possible solutions. This information will be passed to node 5 in the next round of communications*)

node 5 locating...      (*As in previous round of location determination*)

from nodes 2 & 6 node 5 located at either:

20   x = 148, y = 170 or x = 0, y = 302

from nodes 2 & 6 node 5 located at either:

x = 71, y = 394 or x = 237, y = 286

node 6 locating...

25   from nodes 2 & 3 node 6 located at either:

x = 32, y = 189 or x = 188, y = 393

node 7 locating...

from nodes 2 & 3 node 7 located at either:

30   x = 28, y = 336 or x = 45, y = 359

node 8 locating...

from nodes 5 & 6 node 8 located at either:  
**node 6)**

$x=23, y=117$  or  $x=46, y=260$

from nodes 5 & 6 node 8 located at either:  
**5 1(of 2) of node 6)**

$x=101, y=211$  or  $x=-39, y=172$

from nodes 5 & 6 node 8 located at either:  
**2(of 2) of node 6)**

$x=186, y=466$  or  $x=185, y=320$

10 from nodes 5 & 6 node 8 located at either:  
**2(of 2) of node 6)**

$x=123, y=361$  or  $x=256, y=420$

*(The combinations of positions 3 or 4 of node 5 with position 2 of node 6 and positions 1 or 2 of node 5 with position 2 of node 6 are incapable of producing solutions)*

15

node 11 locating...

from nodes 1 & 5 node 11 located at either:  
**1(of 4) of node 5)**

20  $x=235, y=51$  or  $x=287, y=122$

*(positions 2-4 of node 5 produce no solutions)*

node 12 locating...

from nodes 5 & 6 node 12 located at either:

25 **1(of 2) of node 6)**

$x=65, y=131$  or  $x=82, y=233$

from nodes 5 & 6 node 12 located at either:

**1(of 2) of node 6)**

$x=71, y=243$  or  $x=-29, y=215$

30 from nodes 5 & 6 node 12 located at either:  
**2(of 2) of node 6)**

$x=147, y=445$  or  $x=146, y=341$

from nodes 5 & 6 node 12 located at either:  
**2(of 2) of node 6)**

*(posn 1(of 4) of node 5 and posn 1(of 2)*

*(posn 2(of 4) of node 5 and posn*

*(posn 3(of 4) of node 5 and posn*

*(posn 4(of 4) of node 5 and posn*

*(posn 1(of 1) of node 1 and posn*

*(posn 1(of 4) of node 5 and posn*

*(posn 1(of 4) of node 5 and posn*

*(posn 2(of 4) of node 5 and posn*

*(posn 3(of 4) of node 5 and posn*

*(posn 4(of 4) of node 5 and posn*

$x=158, y=333$  or  $x=253, y=376$

(As node 8)

UPDATING.....

- 5 Node 1 already fixed near  $x=275, y=76$
- Node 2 already fixed near  $x=118, y=285$
- Node 3 already fixed near  $x=88, y=308$
- updating node 4s # of positions to 4 (127, 64; 243, 221; 183, 192; 320, 217)
- updating node 5s # of positions to 4 (148, 170; 0, 302; 71, 394; 237, 286)
- 10 updating node 6s # of positions to 2 (32, 189; 188, 393)
- updating node 7s # of positions to 2 (28, 336; 45, 359)
- updating node 8s # of positions to 8 (23, 117; 46, 260; 101, 211; -39, 172; 186, 466; 185, 320; 123, 361; 256, 420)
- updating node 11s # of positions to 2 (235, 51; 287, 122)
- 15 updating node 12s # of positions to 8 (65, 131; 82, 233; 71, 243; -29, 215; 147, 445; 146, 341; 158, 333; 253, 376)
- located = 3, partial = 7

20

*Fourth round of location determination:*

node 4 locating...

from nodes 1 & 5 node 4 located at either: (posn 1(of 1) of node 1 and posn 1(of 4) of node 5)

25  $x=127, y=64$  or  $x=243, y=221$

from nodes 1 & 5 node 4 located at either: (posn 1(of 1) of node 1 and posn 4(of 4) of node 5)

$x=183, y=192$  or  $x=320, y=217$

$x=243 y=221$  is inconsistent (& eliminated)

30  $x=183 y=192$  is inconsistent (& eliminated)

$x=320 y=217$  is inconsistent (& eliminated)

node 5 locating...

from nodes 2 & 6 node 5 located at either: *(posn 1(of 1) of node 2 and posn 1(of 2) of node 6)*

$x=148, y=170$  or  $x=0, y=302$

from nodes 2 & 6 node 5 located at either: *(posn 1(of 1) of node 2 and posn*

5 *2(of 2) of node 6)*

$x=71, y=394$  or  $x=237, y=286$

$x=0 y=302$  is inconsistent *(& eliminated)*

$x=71 y=394$  is inconsistent *(& eliminated)*

$x=237 y=286$  is inconsistent *(& eliminated)*

10

node 6 locating...

from nodes 2 & 3 node 6 located at either:

$x=32, y=189$  or  $x=188, y=393$

15 node 7 locating...

from nodes 2 & 3 node 7 located at either:

$x=28, y=336$  or  $x=45, y=359$

node 8 locating...

20 from nodes 4 & 6 node 8 located at either: *(posn 1(of 4) of node 4 and posn 1(of 2) of node 6)*

$x=23, y=117$  or  $x=104, y=178$

from nodes 4 & 6 node 8 located at either: *(posn 2(of 4) of node 4 and posn 2(of 2) of node 6)*

25  $x=182, y=321$  or  $x=235, y=337$

from nodes 4 & 6 node 8 located at either: *(posn 3(of 4) of node 4 and posn 1(of 2) of node 6)*

$x=81, y=135$  or  $x=78, y=245$

$x=104 y=178$  is inconsistent *(& eliminated)*

30  $x=182 y=321$  is inconsistent *(& eliminated)*

$x=235 y=337$  is inconsistent *(& eliminated)*

$x=81 y=135$  is inconsistent *(& eliminated)*

$x=78 y=245$  is inconsistent *(& eliminated)*

*(The choice to locate using nodes 4 & 6 here instead of nodes 5 & 6 as was done in round 3 is purely arbitrary. In this case it is true that there are only 6 possible solutions to the combination of nodes 4 & 6 (of which 5 are subsequently eliminated) as opposed to 8 for nodes 5 & 6. However, there are 16 ( $N=2$ ,  $M=4$ ,  $2NM=16$ ) possible solutions to the equations produced by nodes 4 & 6 based on the information available to node 8, the same number as is possible from nodes 5 & 6. It is only by attempting to solve these equations that node 8 is able to determine that not all of the solutions are REAL (i.e. complex solutions are those solutions whereby the circles do not intersect). It is by luck rather than judgment that node 8 has chosen to initially find real solutions to the equations created by nodes 4 & 6 (6 Real, 10 complex solutions) rather than those from nodes 5 & 6 (8 Real, 8 complex), and then work to eliminate them. In any case, the result would be the same with nodes 4 & 6 the 6 possible solutions have 5 eliminated, if the 8 possible solutions of nodes 5 & 6 were calculated, 7 would be eliminated leaving the same solution.)*

node 9 locating...

from nodes 1 & 11 node 9 located at either: *(posn 1(of 1) of node 1 and posn 1(of 2) of node 11)*

20  $x=234, y=-32$  or  $x=160, y=88$

from nodes 1 & 11 node 9 located at either: *(posn 1(of 1) of node 1 and posn 2(of 2) of node 11)*

$x=230, y=182$  or  $x=366, y=147$

25 node 10 locating...

from nodes 1 & 11 node 10 located at either: *(posn 1(of 1) of node 1 and posn 1(of 2) of node 11)*

$x=232, y=27$  or  $x=212, y=60$

from nodes 1 & 11 node 10 located at either: *(posn 1(of 1) of node 1 and posn 2(of 2) of node 11)*

$x=272, y=141$  or  $x=309, y=131$

node 11 locating...

from nodes 1 & 5 node 11 located at either: *(posn 1(of 1) of node 1 and posn 1(of 4) of node 5)*

x=235, y=51 or x=287, y=122

5

node 12 locating...

from nodes 4 & 6 node 12 located at either: *(posn 1(of 4) of node 4 and posn 1(of 2) of node 6)*

10 x=65, y=131 or x=79, y=142

from nodes 4 & 6 node 12 located at either: *(posn 3(of 4) of node 4 and posn 1(of 2) of node 6)*

x=95, y=167 or x=94, y=214

x=79 y=142 is inconsistent

15 x=95 y=167 is inconsistent

x=94 y=214 is inconsistent

UPDATING.....

20 Node 1 already fixed near x=275, y=76

Node 2 already fixed near x=118, y=285

Node 3 already fixed near x=88, y=308

updating node 4s # of positions to 1

Node 4 fixed near x=127, y=64

25 updating node 5s # of positions to 1

Node 5 fixed near x=148, y=170

updating node 6s # of positions to 2 *(32,189; 188,393)*

updating node 7s # of positions to 2 *(28,336; 45,359)*

updating node 8s # of positions to 1

30 Node 8 fixed near x=23, y=117

updating node 9s # of positions to 4 *(234,-32; 160,88; 230,182; 366,147)*

updating node 10s # of positions to 4 *(232,27; 212,60; 272,141; 309,131)*

updating node 11s # of positions to 2 *(235,51; 287,122)*

updating node 12s # of positions to 1

Node 12 fixed near  $x=65, y=131$

located = 7, partial = 5

5

*Fifth Round of location determination:*

node 6 locating...

10 from nodes 2 & 3 node 6 located at either:

$x=32, y=189$  or  $x=188, y=393$

$x=188, y=393$  is inconsistent

node 7 locating...

15 from nodes 2 & 3 node 7 located at either:

$x=28, y=336$  or  $x=45, y=359$

node 9 locating...

from nodes 1 & 11 node 9 located at either:

20  $x=234, y=-32$  or  $x=160, y=88$

from nodes 1 & 11 node 9 located at either:

$x=230, y=182$  or  $x=366, y=147$

node 10 locating...

25 from nodes 1 & 11 node 10 located at either:

$x=232, y=27$  or  $x=212, y=60$

from nodes 1 & 11 node 10 located at either:

$x=272, y=141$  or  $x=309, y=131$

30 node 11 locating...

from nodes 1 & 5 node 11 located at either:

$x=235, y=51$  or  $x=287, y=122$

## UPDATING.....

Node 1 already fixed near  $x=275, y=76$

Node 2 already fixed near  $x=118, y=285$

Node 3 already fixed near  $x=88, y=308$

5 Node 4 already fixed near  $x=127, y=64$

Node 5 already fixed near  $x=148, y=170$

updating node 6s # of positions to 1

Node 6 fixed near  $x=32, y=189$

updating node 7s # of positions to 2 (28,336; 45,359)

10 Node 8 already fixed near  $x=23, y=117$

updating node 9s # of positions to 4 (234,-32; 160,88; 230,182; 366,147)

updating node 10s # of positions to 4 (232,27; 212,60; 272,141; 309,131)

updating node 11s # of positions to 2 (235,51; 287,122)

Node 12 already fixed near  $x=65, y=131$

15 located = 8, partial = 4

*Sixth Round of location determination:*

node 7 locating...

20 from nodes 2 & 3 node 7 located at either:  
 $x=28, y=336$  or  $x=45, y=359$   
 $x=45, y=359$  is inconsistent

node 9 locating...

25 from nodes 1 & 11 node 9 located at either:  
 $x=234, y=-32$  or  $x=160, y=88$   
from nodes 1 & 11 node 9 located at either:  
 $x=230, y=182$  or  $x=366, y=147$

30 node 10 locating...  
from nodes 1 & 11 node 10 located at either:  
 $x=232, y=27$  or  $x=212, y=60$   
from nodes 1 & 11 node 10 located at either:

$x=272, y=141$  or  $x=309, y=131$

node 11 locating...

from nodes 1 & 5 node 11 located at either:

5  $x=235, y=51$  or  $x=287, y=122$

UPDATING.....

Node 1 already fixed near  $x=275, y=76$

Node 2 already fixed near  $x=118, y=285$

10 Node 3 already fixed near  $x=88, y=308$

Node 4 already fixed near  $x=127, y=64$

Node 5 already fixed near  $x=148, y=170$

Node 6 already fixed near  $x=32, y=189$

updating node 7s # of positions to 1

15 Node 7 fixed near  $x=28, y=336$

Node 8 already fixed near  $x=23, y=117$

updating node 9s # of positions to 4 (234,-32; 160,88; 230,182; 366,147)

updating node 10s # of positions to 4 (232,27; 212,60; 272,141; 309,131)

updating node 11s # of positions to 2 (235,51; 287,122)

20 Node 12 already fixed near  $x=65, y=131$

located = 9, partial = 3

*No further improvements possible.*

## CLAIMS

1. A method of obtaining positional information about individual wireless devices within a wireless ad-hoc network including a plurality of position determining devices in which each position determining device includes means for estimating the distance between itself and any other similar device forming part of the network which is within range, the method including the steps of:
  - i) each position determining device receiving a broadcast message from each other similar device in range specifying, if known, the respective broadcasting device's position or series of possible positions;
  - ii) each position determining device attempting to measure its distance from each other similar device in range;
  - iii) each position determining device calculating, if it has sufficient information, its position, or a series of possible positions and storing this information;
  - 15 and
  - iv) each position determining device broadcasting to each other similar device in range, if known, its position or series of possible positions determined in step iii.
2. A method according to claim 1 wherein the position determining devices employ one or both of sonar and radar techniques for determining their distance from neighbouring position determining device.
3. A method according to either preceding claim wherein the means for estimating the distance between itself and any other similar device of one or more of the position determining devices is non-rotationally symmetrical, whereby certain ambiguities in the possible positions of said one or more of the position determining devices can be resolved or avoided.
4. A method according to claim 3 wherein the or each distance estimating means comprises a first and second pair of a transmitter and a receiver, and wherein the first pair is able to transmit and receive signals only within a first sector of a circle centred around the respective device and approximately in the plane of the network of devices, and the second pair is able to transmit and receive signals only

within a second sector of the circle, wherein the first and second sectors do not overlap one another.

5. A method according to any preceding claim including the step of informing a  
5 minority of the position determining devices of their position independently of the  
other devices in the network.

6. A method according to claim 5 wherein at least three devices are  
independently informed of their position.

10

7. A method according to claim 5 or 6, wherein at least two devices which are  
in range of a third device are independently informed of their position.

15

8. A method according to claim 5, 6 or 7 wherein no more than twenty five per  
cent of the devices are independently informed of their position.

9. A method of operating a wireless device for use in forming, together with a  
plurality of other similar devices, a wireless ad-hoc network, the method comprising  
the steps of:

20

i) listening for a broadcast message from each other similar device in range  
specifying the respective broadcasting device's position or series of possible  
positions;

25

ii) attempting to measure its distance from each other similar device in range;

iii) calculating, if it has sufficient information, its position, or a series of

possible positions and storing this information; and

iv) broadcasting to each other similar device in range, if known, its position  
or series of possible positions determined in step iii.

30

10. A carrier medium carrying processor implementable instructions for causing a  
device or devices to carry out the method of any preceding claim during  
implementation of the instructions.

11. A device for use in forming, together with a plurality of other similar devices, a wireless ad-hoc network, the device comprising:

i) a receiver (18, 21, 16) for receiving a broadcast message from each other similar device in range specifying, when known, the respective broadcasting device's 5 position or series of possible positions;

ii) distance measurement means (16, 21, 18, 19, 20) for measuring the device's distance from each other similar device in range;

iii) processing means (16) for calculating, if it has sufficient information, its position, or a series of possible positions and storage means (16) for storing this 10 information; and

iv) a transmitter (16, 21, 18) for broadcasting to each other similar device in range; if known, its position or series of possible positions determined by the processing means and stored in the storage means.

## ABSTRACT

Method and Apparatus for locating devices

A method of obtaining positional information about individual wireless devices (1-12) within a wireless ad-hoc network including a plurality of position determining devices(1-12) in which each position determining device includes means for estimating the distance between itself and any other similar device forming part of the network which is within range. The method includes the steps of:

- 5     i) each position determining device receiving a broadcast message from each other similar device in range specifying, if known, the respective broadcasting device's position or series of possible positions;
- 10    ii) each position determining device attempting to measure its distance from each other similar device in range;
- 15    iii) each position determining device calculating, if it has sufficient information, its position, or a series of possible positions and storing this information; and
- iv) each position determining device broadcasting to each other similar device in range, if known, its position or series of possible positions determined in step iii.

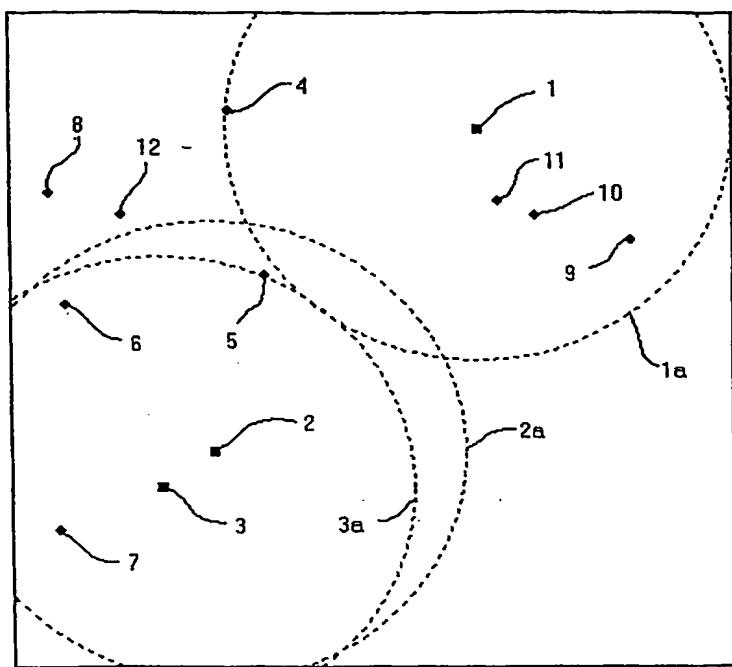


Figure 1

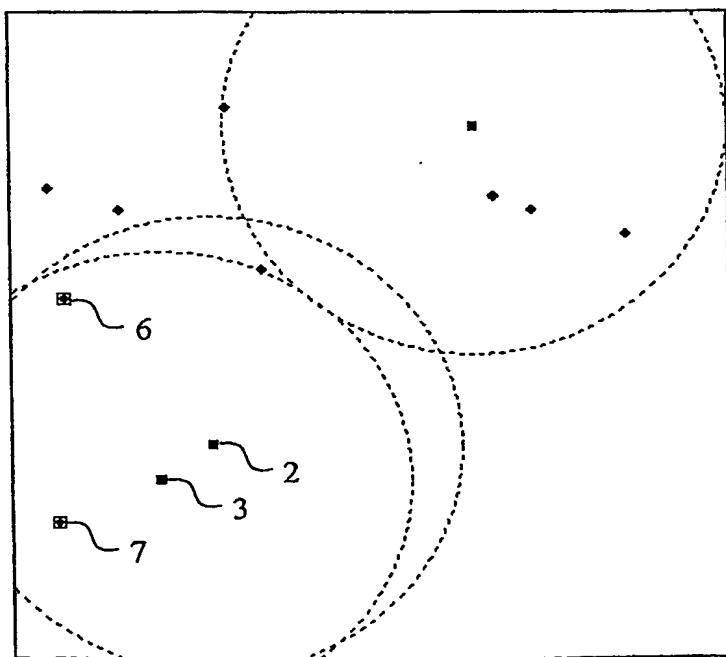


Figure 2

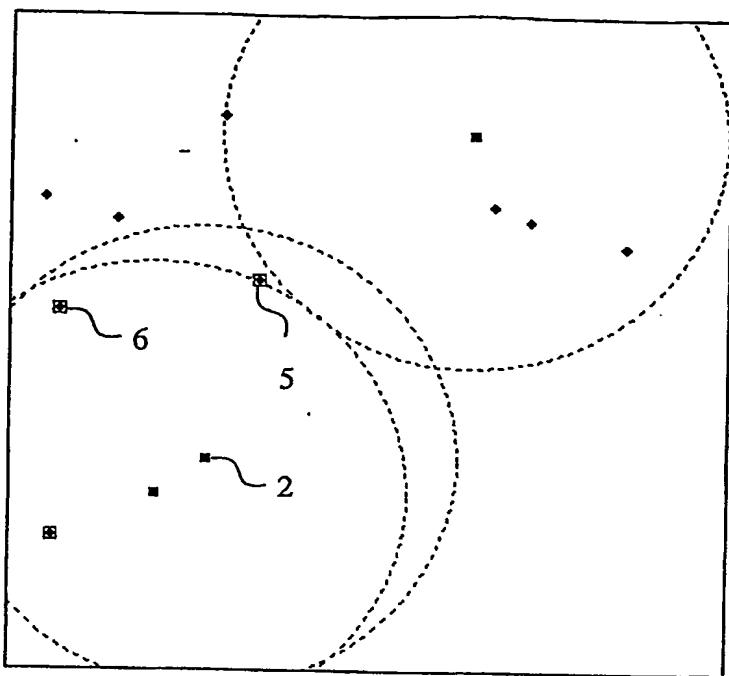


Figure 3

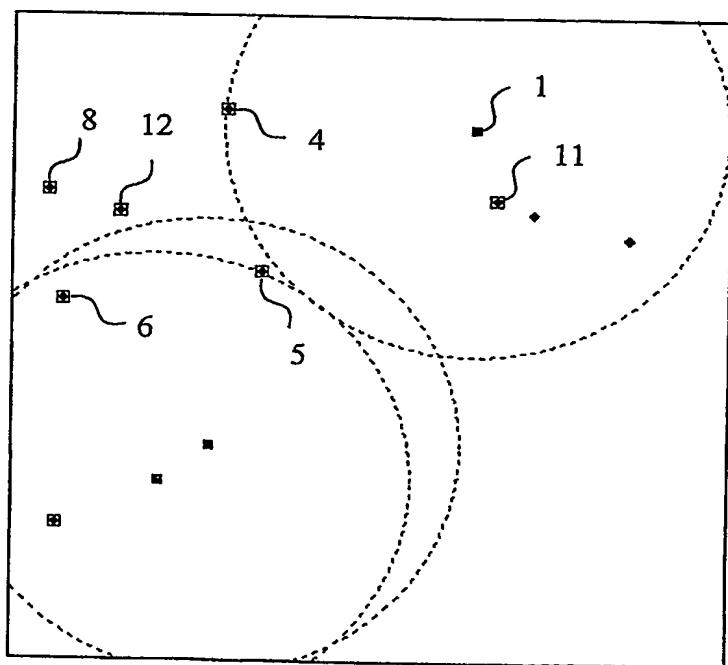


Figure 4

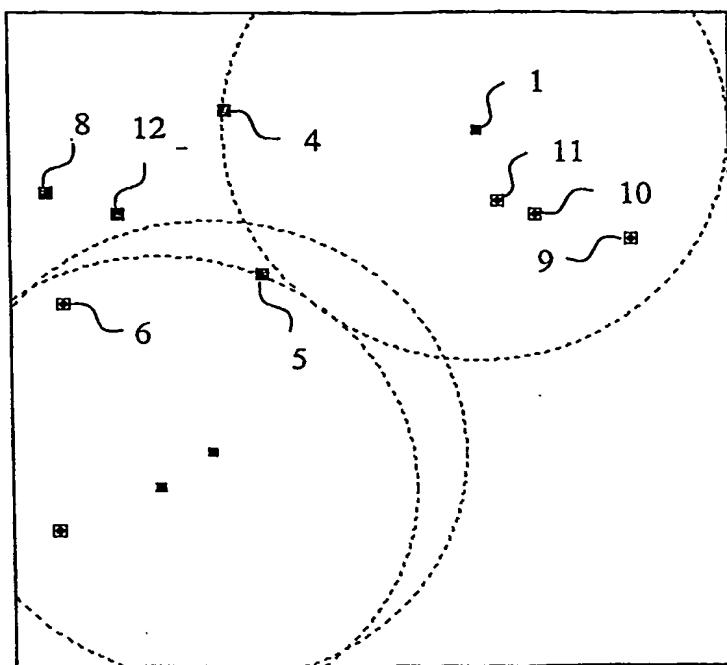


Figure 5

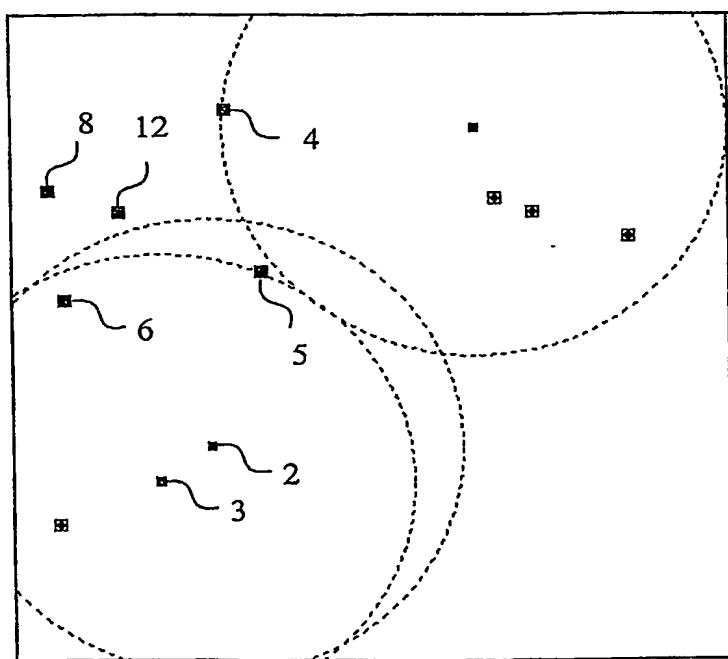


Figure 6

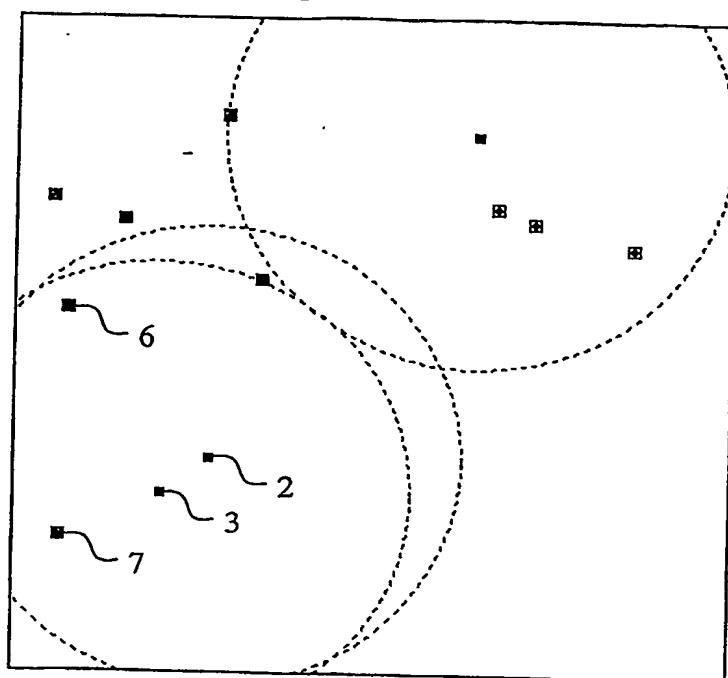


Figure 7

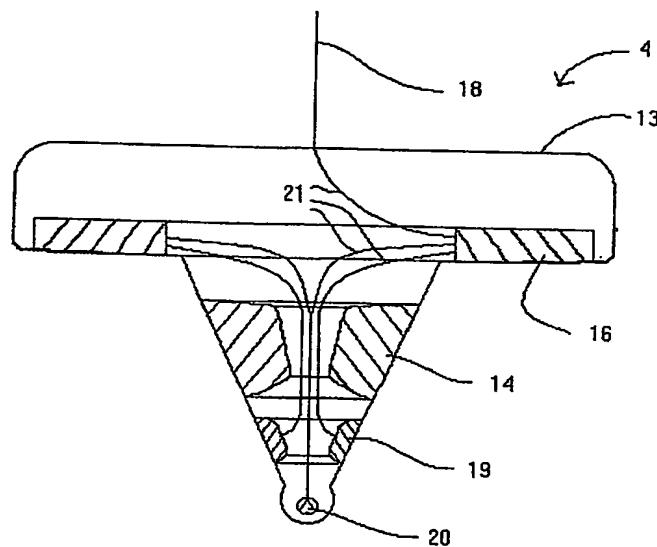


Figure 8